A SOLID-STATE ULTRASONIC IMAGE CONVERTER

ROBERT JOSEPH LARKIN

A SOLID-STATE ULTRASONIC IMAGE CONVERTER

by

Robert Joseph Larkin
Lieutenant, United States Navy
B.S., Drexel Institute of Technology, 1959

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ELECTRICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
June 1968

ABSTRACT

Acoustical techniques can be used to obtain underwater images at distances greater than those currently obtained by optical means. Electronic scanning of a mosaic transducer at the focal plane of an acoustic lens enables target image reproduction on a cathode ray tube using intensity modulation.

Previous work in developing the required amplifier and gating circuitry has resulted in systems with excessive cabling and of excessive size. This report is a study of the design of a 16-channel printed circuit board immediately adjacent to a linear transducer array so as to eliminate cabling. Microelectronic devices are used to confine all electronics to a 0.26 x 0.26 inch cross-section for each channel. A 32 x 32 element mosaic at 250 kHz could be scanned by a package no larger than 9x9x6 inches. A discussion of performance, size, and costs is included.

TABLE OF CONTENTS

[illegible]

LIST OF ILLUSTRATIONS

ACKNOWLEDGEMENTS

This project was suggested by Professor G. L. Sackman who acted as advisor. Sincere appreciation is expressed for his patience and many hours of helpful discussions.

Also without the aid of Mr. Hollis Oren, construction of the 16-channel printed circuit board would have been virtually impossible.

CHAPTER I

INTRODUCTION

Acoustical techniques can be used to obtain underwater images at distances greater than those currently obtained by optical means. One such technique is to transmit an ultrasonic pulse, and then scan the area with a receiving transducer system at the focal plane of an acoustic lens. The induced transducer voltages are then amplified and switched as necessary to reproduce the target's image on a TV type screen for viewing.

Design and experimental results of an existing system are reported in theses by Lt. K. G. Robinson (1) and Lt. A. F. Barta (2), and a paper presented to the Acoustical Society of America by Sackman, et al. (3) Their ultrasonic image system uses a 9x9 transducer mosaic at the focal plane. Each element of the mosaic is connected to a miniature 450 kHz i-f amplifier with a diode detector, FET switching circuitry, scanning logic network, and an equalizing potentiometer. Because of the physical separation of transducers, amplifiers, and logic network, excessive cabling is required. This cabling not only introduces excessive crosstalk, but seriously reduces the reliability of the system.

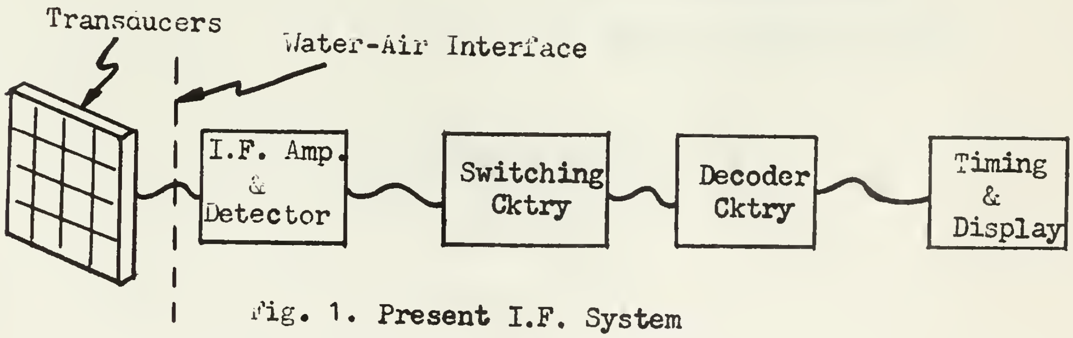


Fig. 1. Present I.F. System
Cables connect blocks in the system.

A 32x32 mosaic is near the minimum required to reproduce images. For such a large system it was believed that a quantum jump in performance might be achieved by packaging entire linear arrays of channels on printed circuit boards to reduce the cabling. Furthermore, the transducers were to be mounted alongside the printed circuit board so as to remove all cabling except that which passes from the sonar circuitry to the power supply, video, and timing circuits.

Space requirements dictate that the engineer cannot use the present i-f strips but must look for a solution using integrated circuits. The purpose of this project was to develop an operational sixteen channel linear module which would allow an entire 32x32 transducer array and its associated circuitry to be encapsulated in a submersible package no larger than the conceptual version described in Figure 2.

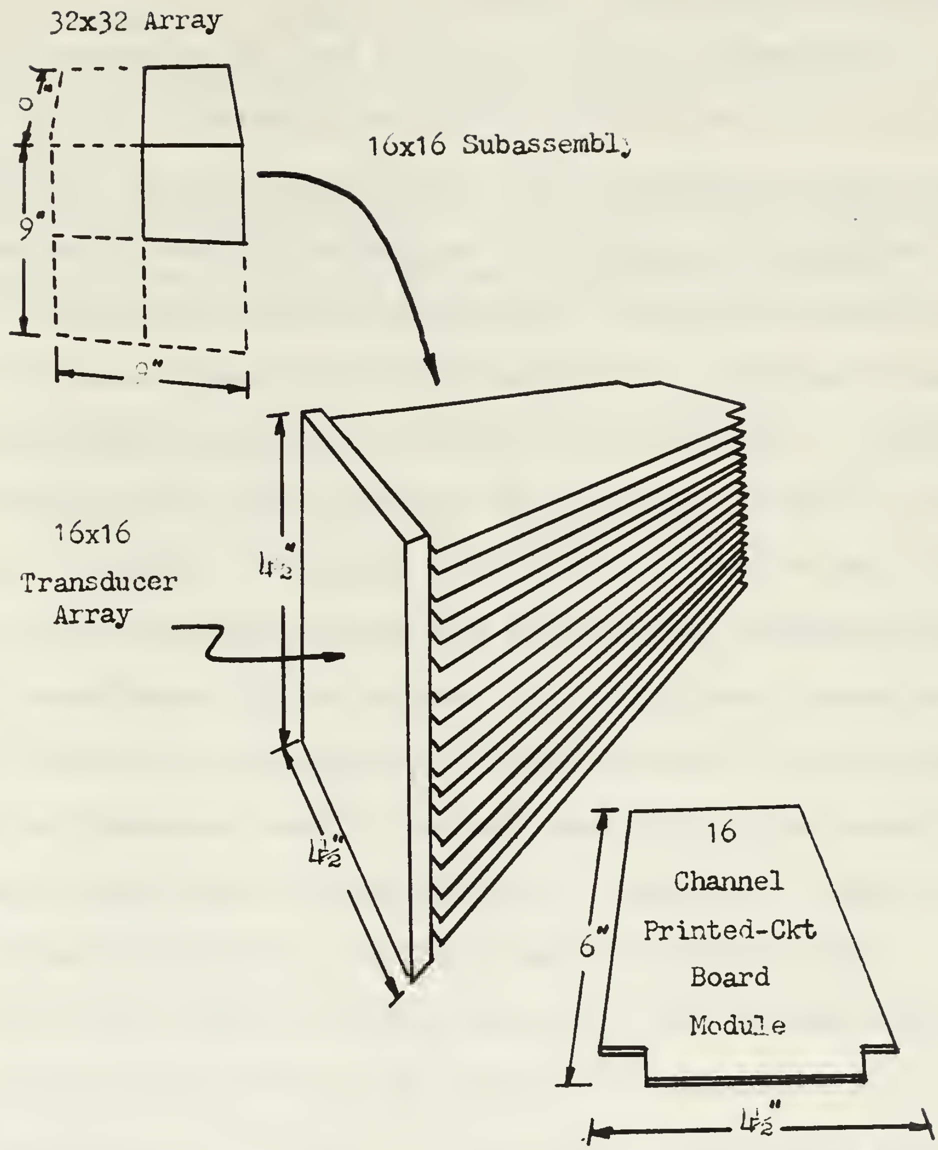


Fig. 2. Conceptual Design

CHAPTER II

DESIGN CONSTRAINTS

Three basic constraints characterize this project. These are good performance, small size, and low cost.

Performance constraints are such that the device specifications must at least match those of the existing system, i.e. a 40 db signal gain must be available at the output of the detector. Amplifier linearity is not required but some saturation above 10 mv peak input is desired to attenuate highlights from direct reflection. For adequate sensitivity, the minimum discernible signal should be in the region of 0.1 mv peak input, giving an information dynamic range of 0.1 to 10 mv. A broad band RC amplifier rather than a tuned i-f type can be used by relying on the transducer crystal for frequency discrimination, and employing wide band modulation on the projector. Performance stability is also required so that potentiometer equalizers are avoided. Each channel should respond alike to an input signal. This requires the use of various feedback schemes throughout the channel circuitry. Furthermore, crosstalk between channels must be minimized.

Size constraints are imposed by the operating frequency. A compromise must be made between range and resolution of the system. For the best resolution we would like the crystal array to be in a closest-packed arrangement. Crystal size is related to the frequency approximately by equation (1).

$$f_{resonant} = \frac{\text{velocity of propagation}}{2 \times \text{crystal length}} \qquad (1)$$

Therefore, a 450 kHz crystal would be less than 0.16 inches. This necessitates seeking a lower frequency so that size requirements can be satisfied with currently available off-the-shelf hardware. At 250 kHz a PZT transducer would be approximately 0.250 inches long. Components are available no larger than 0.26 inches in any two dimensions. Hence the requirements can be satisfied with only a factor of 2 decrease in resolution.

Since the end goal is a 32 x 32 array, a limit of $10 per channel was desired to insure that the system be economically feasible.

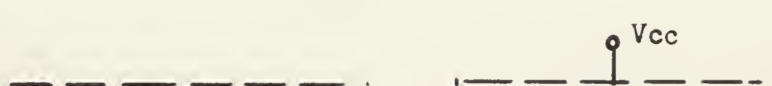
CHAPTER III

DESCRIPTION OF AMPLIFIER AND DETECTOR CIRCUITRY

The need for 40 db gain requires the use of an integrated circuit amplifier. This device realizes the gain of a multistage transistor amplifier resulting in both a savings in space and production handling. For such a device to be suitable, it must be operable at the desired frequency with the minimum of external circuitry. The necessity for lead/lag networks complicates the circuit causing an increase in both channel size and cost. Fairchild Semiconductor Corporation's uA702C was found most suitable for this purpose. Most other available IC amplifiers were ruled out either due to excessive cost or external frequency compensating networks required. The uA702C differential amplifier not only provides the necessary gain but requires only a feedback resistor as an external component at 250 kHz, and saturates at a peak output swing depending on the applied bias voltages. Furthermore, the uA702C is available in a flat-pack configuration with the largest dimension of 0.26 inches. The gain is quite temperature stable, falling off about 3 db at 125° C and rising only 1.2 db at -55° C. This small change in gain makes the amplifier quite useful in this application requiring extreme closed-loop gain equality between channels.

The differential amplifier with its non-inverting input to ground produces satisfactory gain with a 100K ohm feedback resistor (see Figure 3). A 2.2K ohm load resistor was found experimentally to be optimum. Any increase thereof produces spiking at the detector output whereas any decrease causes reduction in the output signal. A 270 pf capacitor is used to couple the amplifier and detection circuitry. It is found that overall gain can be improved by increasing the capacitance and decreasing the value of the bias resistor in the detector stage but that this resulted in reducing the input-output signal response by saturating the amplifier with lower voltage inputs.

The detector stage is an emitter follower circuit with a 0.1 uf capacitor storage output and a 27K ohm base bias resistor. The resistor is needed as a feedback technique to accomodate variations in current gain between transistors. Using 1M ohm, the output varies from 5.9 to 3.7 volts, whereas reduction to a 27K ohm resistor allows only a 0.1 volt variation for a 3.5 volt output.



CHAPTER IV

DESCRIPTION OF ANALOG SIGNAL SWITCHING CIRCUITRY

The basic circuit as discussed in Barta's paper (2) was adopted (see Figure 4).

The FET gate voltage is normally maintained at some value above pinch-off (Vp plus 2 volts) to insure cut-off. By driving the gate voltage down to approximately 4 volts (at about Vp/2) even the lowest signal is allowed to pass through to the drain. The gate voltage, and also the transistor collector voltage, is controlled by pulsing the base of the driving transistor.

Two changes were made to Barta's scheme to better meet the channel design constraints.

1. The emitter resistor was increased from 270 ohm to 1000 ohm to reduce the current drain on the power supply for the shift register and to insure against forward biasing of the FET. Otherwise, excessive discharge of the detector capacitor will occur causing an attenuation of the output signal.

2. Barta's system required well over 40 devices to develop a trigger for 16 channels. These devices were necessary to provide for a BCD ten-count shift register, a BCD-to-decimal decoder, and logic decoding gates. This system was found much too complicated for the small packaging and good reliability desired. To this end, a Fairchild CCSL 9300 4-bit shift register was selected. For a 16 channel board, four of these are connected in series (see Figure 5). The 9300 is connected to operate in the left shift mode. The scanning pulse, a logical "1", passes sequentially through the register stages at a rate set by the clock pulse frequency (up to 15MHz). This enables one potentially to

sample the outputs of a 32 x 32 array in less than 100 microseconds if desired. Output level of the shift register stages is controlled by the power supply voltage, Vcc, and can vary with Vcc from zero to 3 volts.

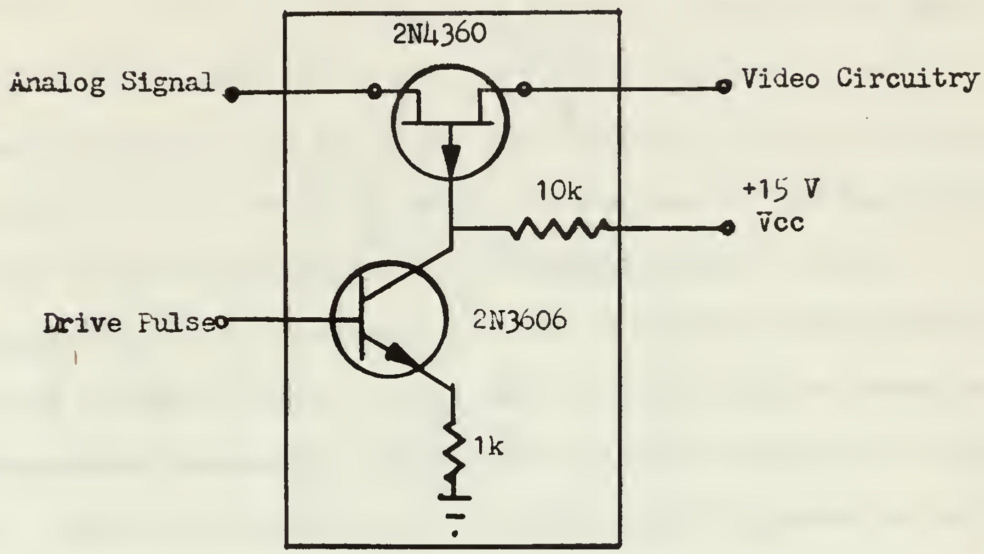


Fig. 4. Analog Switch Circuitry for One Channel

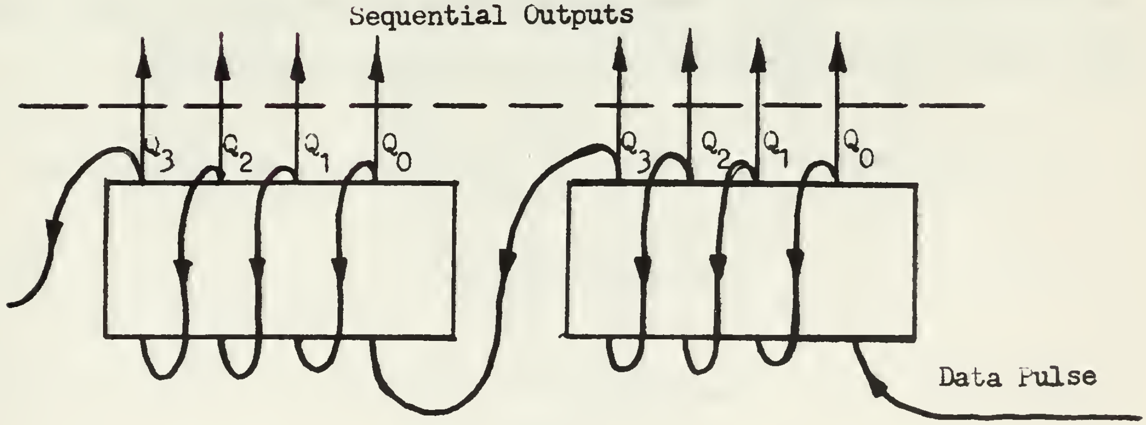


Fig. 5. Series Connection of Shift Registers

CHAPTER V

MULTICHANNEL OPERATION

The single channel design is shown in Figure 6. Sixteen such channels are mounted side-by-side on the printed circuit board, and their outputs are scanned sequentially by the shift register. Waveforms are shown with a common time scale.

The pulse input at (a) from each of the sixteen transducers is amplified 40 db or better. This amplified pulse at (b) is then detected by an emitter follower amplifier and stored on a 0.1 uf capacitor at (c).

When the voltage level at (f) is driven above ground by the output of the shift register, the driving transistor turns on causing its collector voltage at (e) to drop from 15 volts to about 4 volts. The gate of the FET is tied directly to the collector of the transistor so that in turning on the transistor one also turns on the FET. Turning on the FET transfers the source voltage to the drain. While the FET is "on", the detector stage sees a low resistance and partially discharges to ground potential before the next pulse arrives.

The drains of all channels are tied to a common line at (d) providing a sequential signal to be monitored on a video screen. These signals can be used to intensity modulate the cathode ray beam so that an image of the underwater target is produced on the screen.

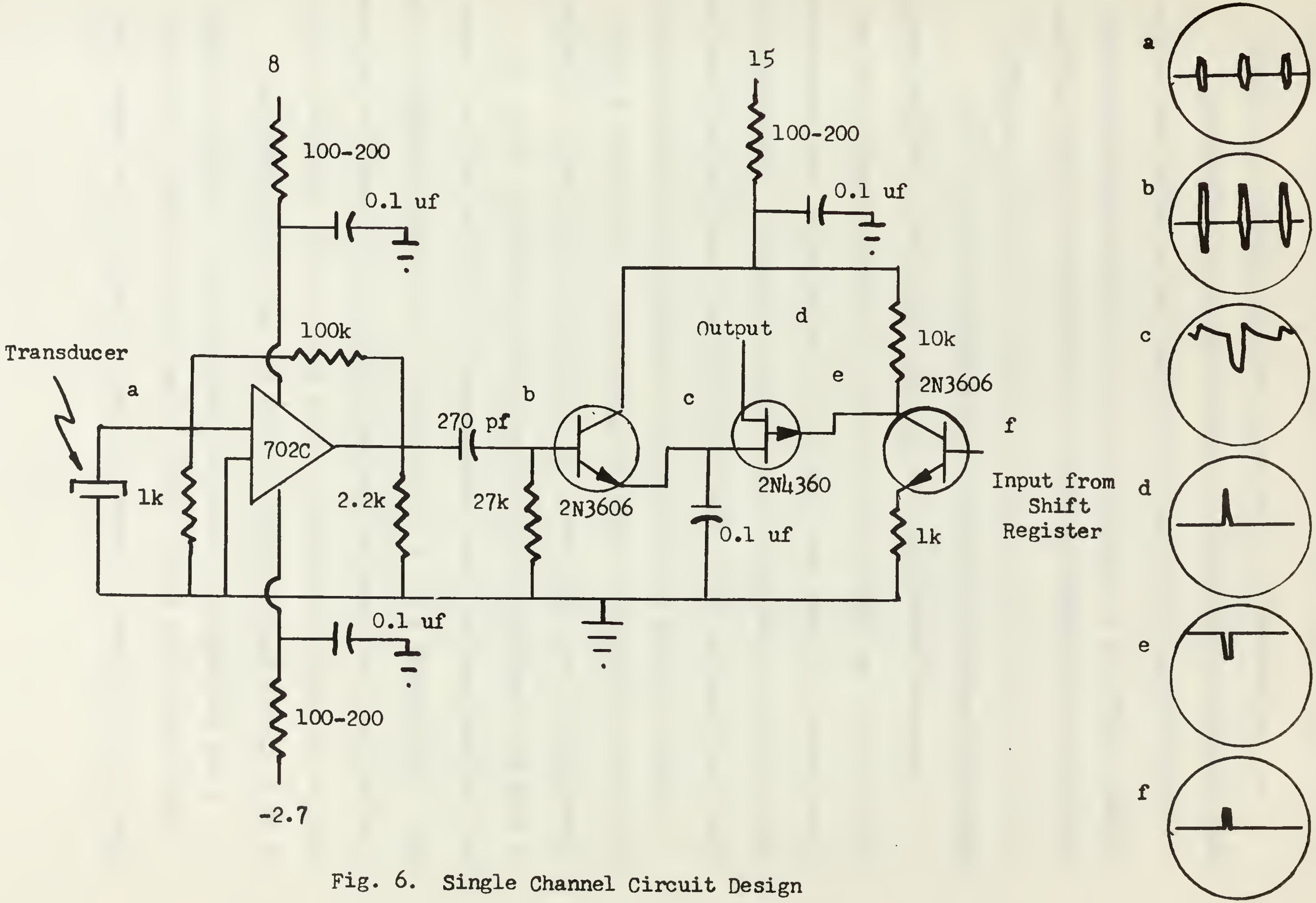


Fig. 6. Single Channel Circuit Design

CHAPTER VI

DESIGN OF THE 16-CHANNEL PROTOTYPE PRINTED CIRCUIT BOARD

The desired result of this study is an operational 16-channel board no larger than about four inches wide and 1/4 inch thick.

A four-channel board was wired to test for crosstalk after a one-channel breadboard arrangement proved to be satisfactory for gain and stability. Measurements indicated that 16 channels could be laid side by side in a space no more than 4.16 inches, and that the largest board-plus-component thickness was 0.26 inches.

A schematic drawing in quadruple size was laid out for 16 channels. Quadruple size was used to allow for ease in spacing common lines and ground busses. It was found that due to the excessive interconnections, jumper wires or double-sided boards would be required. The double-sided board was chosen so as to eliminate additional handwiring and soldering.

Printed circuit board layout was accomplished by applying adhesive black dots and tape to a sheet of clear plastic. After both top and bottom layouts were completed, the two schematics were coded and marked so that the component lead holes would align perfectly. These two 2x2 foot displays were then photo-reduced to yield two 6x6 inch negatives (see Figures 7 and 8 for positives). The camera reduction was not a perfect 6x6 inch negative, but was distorted 1/32 inches in one dimension due to camera inadequacies. This distortion is tolerable as long as it is in the same direction on both top and bottom negatives.

A jig was required during the etching process to insure alignment of both sides of the board. This jig was made by cutting a 6x6 inch space out of a piece of formica the same thickness as the board. The negatives were taped to opposite sides of the formica jig so that the board could be set in the 6x6 inch space and be exposed.

The results of the first board were satisfactory but indicated that some improvements could be made to the masks. Several etched lines on the top mask were found to be too close (minimum spacing of a tape width is recommended). The corrected mask is reproduced as Figure 9.

Holes were machine drilled with a #75 bit for the shift register and amplifier leads, and a #60 bit for all other leads.

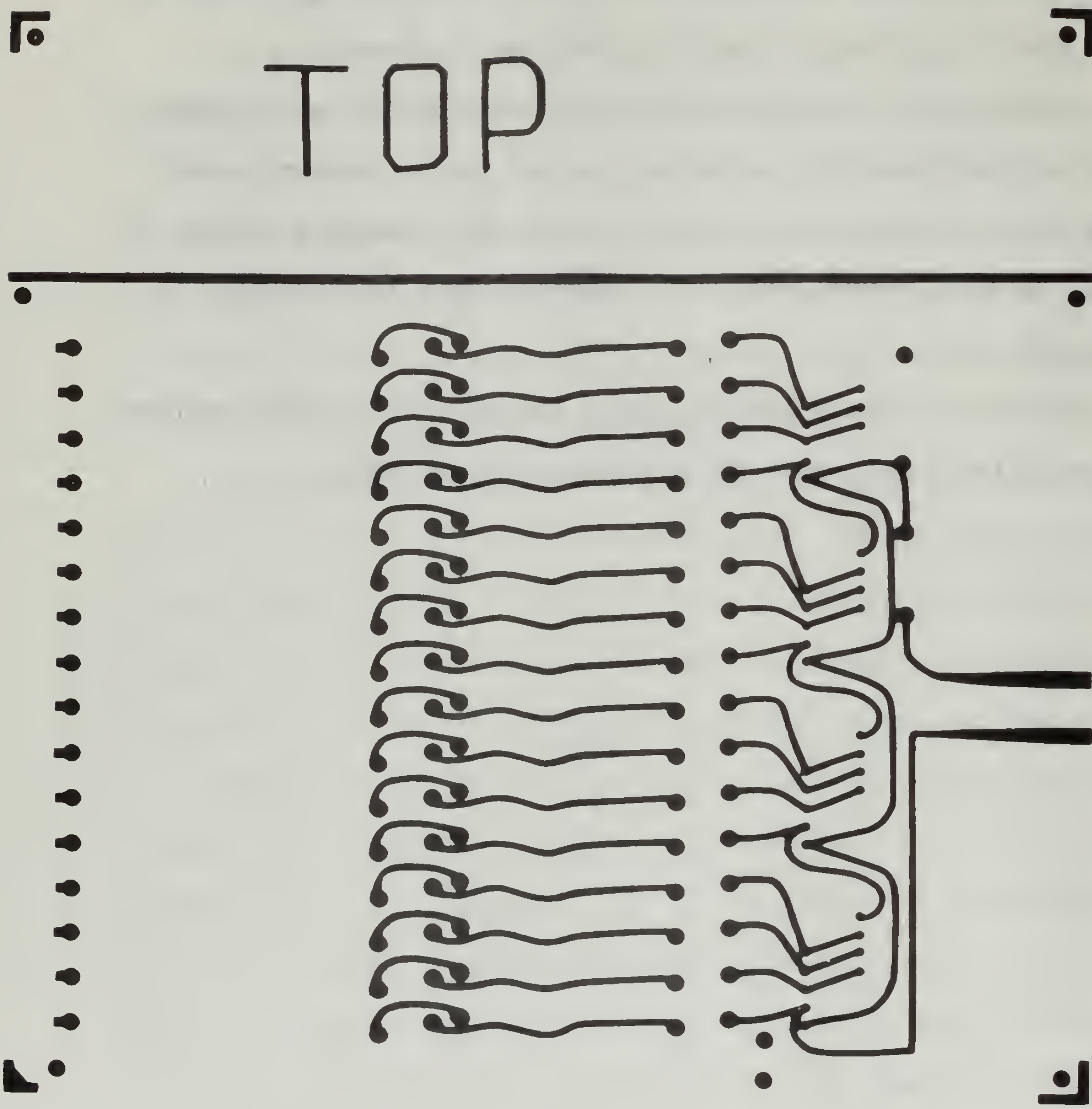


Fig. 7. Printed Circuit Pattern for Top of PC Board (Actual Size)
This was the first attempt.

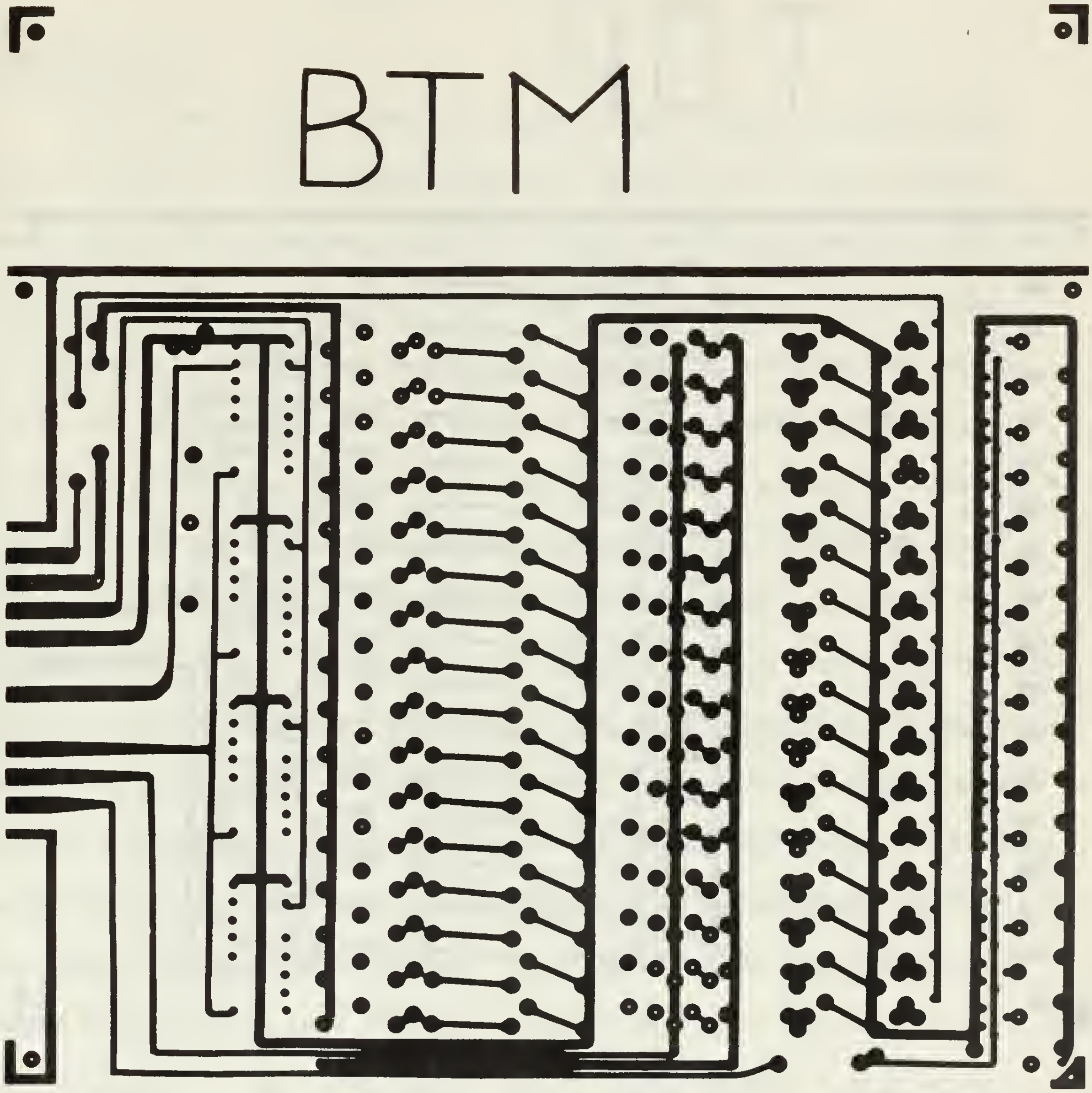


Fig. 8. Printed Circuit Pattern for Bottom of PC Board (Actual Size)

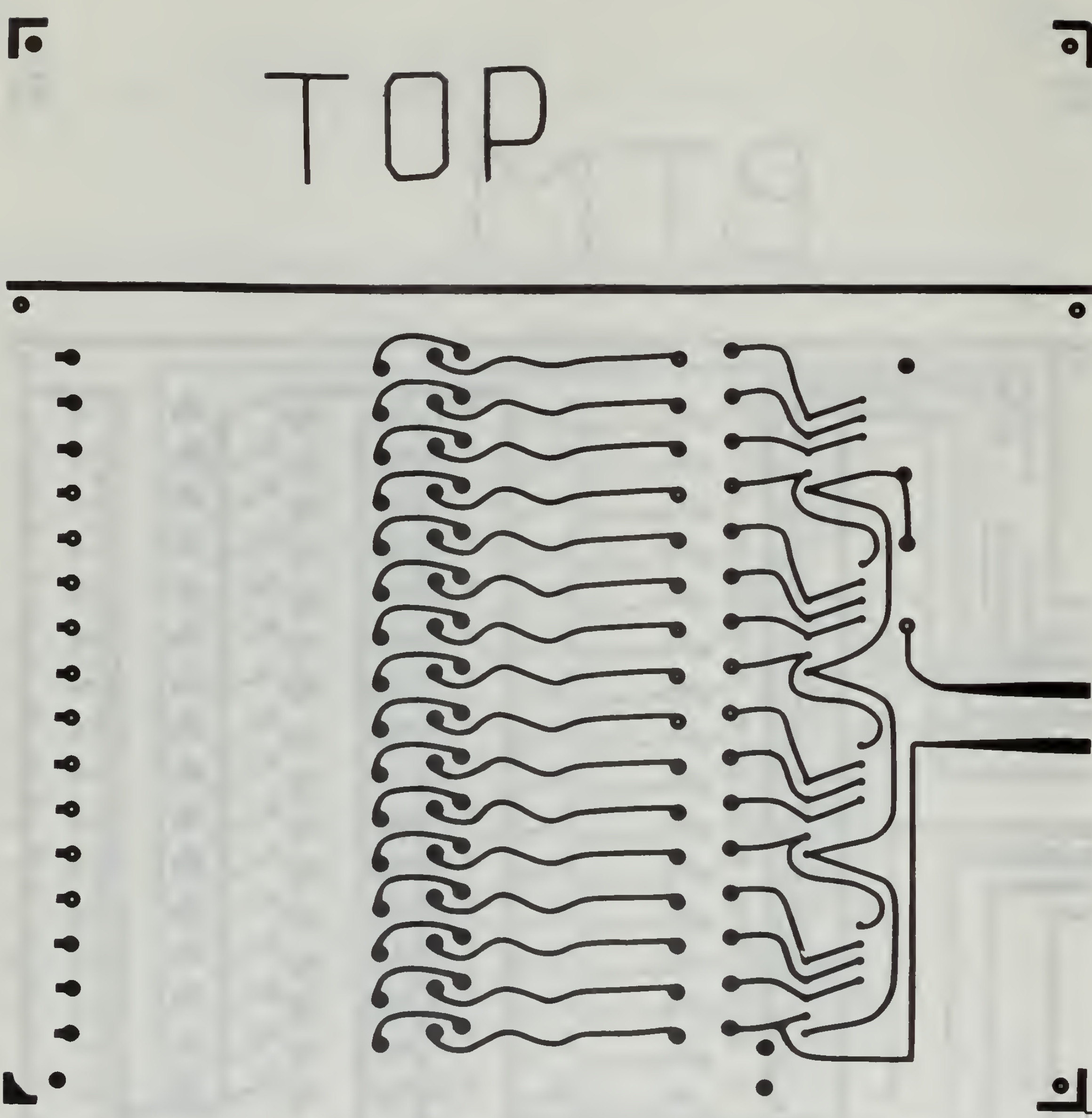


Fig. 9. Printed Circuit Pattern for Top of PC Board (Actual Size)
This was the second attempt.

CHAPTER VII

EXPERIMENTAL RESULTS

Amplification

Measurements were taken by transmitting a signal through water (in a beaker) to a transducer connected to any one of four channels as desired. The peak pulse amplifier input was to be compared with the detector output to determine the voltage gain. Because of detector voltage decay between pulses, and oscilloscope synchronization problems, measurement with pulsed inputs proved to be quite difficult. Therefore, the transmitted signal was changed from pulsed to continuous-wave to insure a non-varying detector output. Figure 10 shows that well over 40 db gain is available for inputs between 0.1 and 30 mv. Measurements of gain at input levels below 0.1 mv were not made due to oscilloscope sensitivity limitations. Use of an attenuator to enable measuring of the lower inputs was aborted since this technique was not of known reliability and would give an uncertain indication of receiver sensitivity. Above 30 mv the amplifier begins to saturate, limiting the output to less than 5 volts. These observations were performed while the amplifier bias voltages were set at -2.7 v and +8 v.

The gain of low level inputs can be significantly increased by increasing the positive bias in the amplifier. This may provide some useful gain control, but is not recommended since higher level inputs will saturate at as much as 15 v output level.

Channel Variation

Some variation appears in the input-output curves of Figure 10. It is believed that these variations are primarily due to the inability

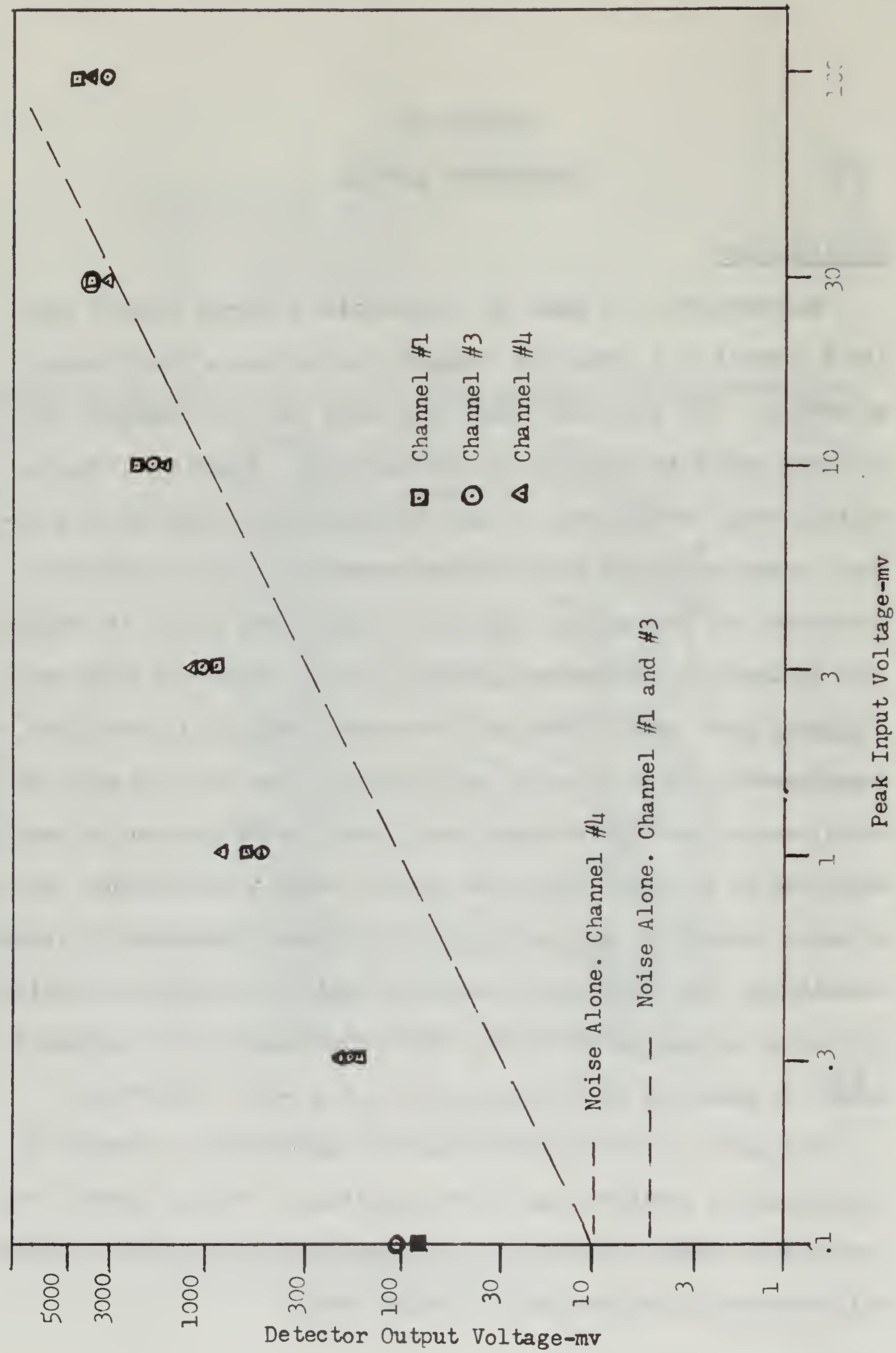


Fig. 10. Output vs Input Voltages of Amplifier-Detector Circuitry

to reset the input signal to the same level for each channel. By applying the input signal directly to the amplifier rather than through the water-transducer interface it was noted that the channel outputs were quite uniform. With a 10 mv input and a 3.4 v output, no more than a 0.2 v difference was noted. Since the detector capacitor will quite possibly discharge to 30% of its peak voltage during the sampling time, a 10% channel variation is not considered significant. Data taken at another time indicated a 4.4 v output with no variation in channel outputs (see crosstalk data).

Noise

The amount of noise produced in a circuit limits its sensitivity. Noise can be measured directly by observing the dc level of the detector output when no signal is applied at the input. These levels are shown on Figure 10 to be 10 mv or less for three channels. Again, these measurements are with the amplifier settings of -2.7 v and +8 v. Any increase of the positive bias voltage causes an increase in output noise as well as output signal (see crosstalk data for noise levels with increased gain). The one noisy channel (68 mv) was thought to be due to a faulty FET. When this FET was replaced, the noise voltage dropped to 8 mv.

Crosstalk

One primary reason for this project was the need to develop a system whereby the crosstalk would be substantially below that of the i-f system previously developed. The i-f system had between -19 and -26 db crosstalk for a 20 mv peak input. By electrically exciting one channel, each of the other three channel outputs was observed for a measure of crosstalk between channels. These measurements were recorded at two different times, once with a reference of 4.4 v output and again with a reference of 3.4 v after channel #2 failed and the noisy FET of channel #3 was replaced. These two sets of data indicated that crosstalk was below the noise level at -50 db or better.

Input-Output Data for Crosstalk Measure.

Data taken with noisy FET:

Input Channel \ Output Channel	1	2	3	4
1	4.4v	10mv	68mv	18mv
2	5mv	4.4v	68mv	18mv
3	4mv	10mv	4.4v	24mv
4	8mv	8mv	68mv	4.4v

Data taken with noisy FET replaced:

Input Channel \ Output Channel	1	2	3	4
1	3.4v	7mv	8mv	10mv
2	5mv	Bad Channel	8mv	9mv
3	5mv		3.2v	9mv
4	5mv		8mv	3.4v

CHAPTER VIII

CONCLUSIONS

A compact solid-state ultrasonic image converter was designed which provides 40 db gain, noise free operation down to less than 0.1 mv input, and virtually no channel crosstalk.

Sixteen channels can be provided on a 4 1/2 x 6 inch printed circuit board. Since the component-plus-board thickness is no more than 0.26 inches, 16 boards can be sandwiched together within a 4 1/4 inch space. Such packaging will permit a 32x32 array to be as small as 9 x 9 x 6 inches.

The only cabling present is that providing a common ground, power supply voltages, trigger voltages, and the output line between the receiver array and the shipboard controls.

Present costs (see Appendix B) indicate $13.57 per channel, somewhat more than desired, but not unreasonable. Price trends indicate that microelectronic devices will be available at a much lower cost in the near future. The 9300 shift register has been on the market for less than six months. Additional price reduction might possibly be obtained as the uA702C amplifier finds more marketable applications.

BIBLIOGRAPHY

1. Robinson, K. G. An Experimental Ultrasonic Image System for Underwater Vision. Thesis. Naval Postgraduate School, Monterey, 1967.

2. Barta, A. F. A Time Multiplex Switching System for Visual Display of the Outputs of an Ultrasonic Transducer Array. Thesis. Naval Postgraduate School, Monterey, 1967.

3. Sackman, G. L., A. F. Barta, G. C. Caswell, and K. G. Robinson. "Experimental Ultrasonic Image System for Underwater Use" Journal of Acoustical Society of America, Vol. 42, p. 1186, 1967.

4. Dellegar, W. E. Microelectronic Integrated Circuit Boards: Repair. Naval Electronics Laboratory Center, San Diego, 1967.

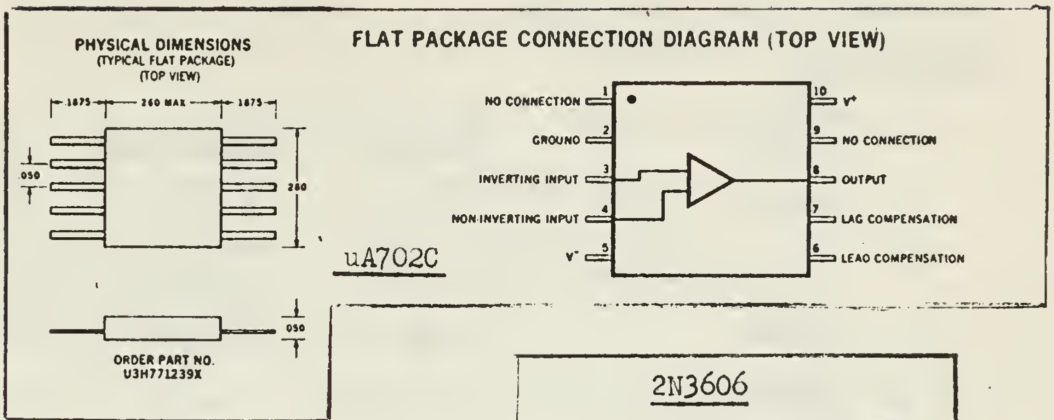
Useful technical data is contained in the following:

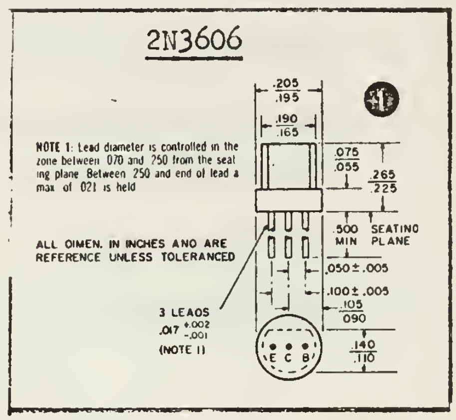
5. Giles, J. N. Fairchild Semiconductor Linear Integrated Circuits Applications Handbook. 1967.

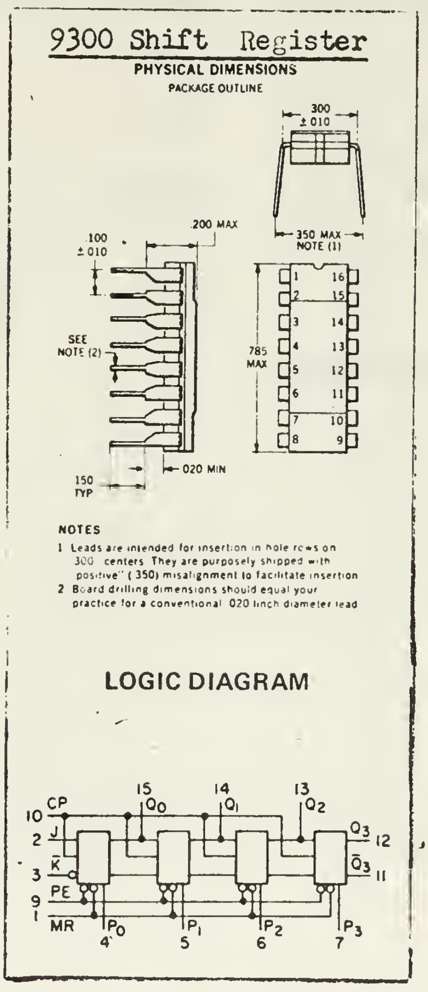
6. Shipley, M. "Analog Switching Circuits Use Field-Effect Devices", Electronics, December 28, 1964, pp. 45-51.

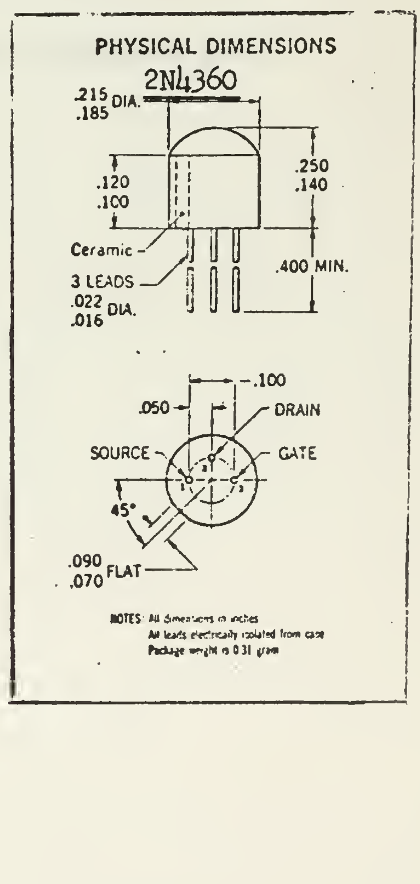
APPENDIX A

PHYSICAL DIMENSIONS AND LEAD CONFIGURATIONS









APPENDIX B

CHANNEL COST

The cost is figured on the basis of production of 6 or more 16-channel boards. These costs do not reflect the price of the printed circuit board.

Device	No. Used	Device Cost	Total Cost
uA702C	16	$ 7.50	$ 120.00
9300	4	14.40	57.60
2N4360	16	.65	10.40
2N3606	32	.30	9.60
0.1 uf Capacitor	20	.44	8.80
270 pf Capacitor	16	.32	5.12
1/8 W Resistors	16	.16	2.56
1/4 W Resistor	84	.027	2.26
			$ 216.34

The resulting channel cost is $13.57.

APPENDIX C

RECOMMENDED TOOLS

Microcircuit device size and power dissipation generates the need for certain tools not usually found in a technicians tool box. The following tools were found to be extremely useful.

Miniature Soldering Iron (less than 10 watts)
Solder Gobbler Iron - a desoldering vacuum system
High Intensity Lamp
Binocular Magnifier (2 1/2 power)

Reference 4 gives a complete list of recommended items for an electronic technician's microelectronic-circuit board repair kit.

INITIAL DISTRIBUTION LIST

		No. Copies
1.	Defense Documentation Center Cameron Station Alexandria, Virginia 22314	20
2.	Library U. S. Naval Postgraduate School, Monterey, California	2
3.	Director of Naval Communications Department of the Navy Washington, D. C. 20350	1
4.	Prof. George L. Sackman Department of Electrical Engineering Naval Postgraduate School Monterey, California 93940	3
5.	LT Robert J. Larkin 361 Dela Vina Avenue Monterey, California 93940	1
6.	Mr. Henry Warner Navy Mine Defense Laboratory Panama City, Florida 32401	1

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Naval Postgraduate School Monterey, California 93940	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

A SOLID-STATE ULTRASONIC IMAGE CONVERTER

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

Thesis

5. AUTHOR(S) *(First name, middle initial, last name)*

LT Robert J. Larkin

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
June 1968	33	6

8a. CONTRACT OR GRANT NO.	9a. ORIGINATOR'S REPORT NUMBER(S)
b. PROJECT NO.	
c.	9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*
d.	

10. DISTRIBUTION STATEMENT

[redacted]

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Naval Postgraduate School Monterey, California 93940

13. ABSTRACT

Acoustical techniques can be used to obtain underwater images at distances greater than those currently obtained by optical means. Electronic scanning of a mosaic transducer at the focal plane of an acoustic lens enables target image reproduction on a cathode ray tube using intensity modulation.

Previous work in developing the required amplifier and gating circuitry has resulted in systems with excessive cabling and of excessive size. This report is a study of the design of a 16-channel printed circuit board immediately adjacent to a linear transducer array so as to eliminate cabling. Microelectronic devices are used to confine all electronics to a 0.26 x 0.26 inch cross-section for each channel. A 32 x 32 element mosaic at 250 kHz could be scanned by a package no larger than 9x9x6 inches. A discussion of performance, size, and costs is included.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6811

Security Classification

A-31408

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Acoustic Imaging						
Ultrasonic						
Ultrasonic Image Converter						
Mosaic Transducer						

DD FORM 1 NOV 65 1473 (BACK)

S/N 0101-807-6821

A-31409